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SUMMARY

An investigation was made of the pilot's ability to control a simulated supersonic transport at a Mach number of 3 and an altitude of 70,000 feet, with emphasis on regions of low stability and damping characteristics. The fixed-base simulator employed no outside visual or motion cues and no outside disturbances. Routine tasks such as maintaining constant altitude, changing altitude, and changing heading were performed. Desirable stick forces and sensitivities were also determined. The investigation was divided into two parts: studies of the longitudinal stability characteristics and of the lateral-directional characteristics. In investigating one mode the stability and damping of the other mode was increased to a "satisfactory" level. This procedure should tend to give more favorable ratings than would be obtained with no improved stability or damping about any axis.

Pilot's ratings of the longitudinal stability and control characteristics were generally "acceptable" (pilot rating of 4) for configurations having short-period frequencies of 0.13 to 0.37 cps, damping ratios of 0.06 to 0.36, and compatible control characteristics. Pilots preferred longitudinal stick sensitivities of 0.1 to 0.2g/in. stick deflection and stick-force gradients of approximately 20 to 40 lb/g normal acceleration.

Configurations having roll time constants up to about 4.7 seconds were acceptable, provided good aileron characteristics were established. However, a decrease in roll time constant from 4.7 sec to 1.8 or 1.4 sec was highly beneficial in improving roll control. The optimum level of aileron-control power gradient (radians/sec^2/radian) for supersonic transport configurations with improved roll damping was similar to that of a present-day turbojet transport in the cruise condition.

INTRODUCTION

The flying qualities of a basic (unaugmented) supersonic transport (SST) in the cruise mode will tend to be marginal. Damping will be low as a result of the low air densities and the slender configuration. Three-axis stability augmentation will no doubt be needed to provide satisfactory flight characteristics. In the event of augmentation failure, however, the pilot must be able to control the unaugmented configuration if completion of the flight is to be expected. Previous investigations have been made to define minimal stability and control levels. Some of these investigations, most of which were not for the SST configuration, tend to define critical areas and methods of investigation. The results of reference 1 point to characteristics which affect pilot opinion in an evaluation of the longitudinal short-period and lateral-directional modes. References 2, 3, and 4 define some desired levels of roll response, lateral control power, and cross-coupling parameters. Studies in reference 5 give a method of defining minimum acceptable stability parameters and also present some "acceptable" and "satisfactory" values of short-period and lateral-directional characteristics for an SST in cruise flight. Although there are much data covering the area of minimum stability, the ratings tend to vary depending upon the characteristics of the particular investigation. Such an instance is shown in the results of references 1 and 6 where the more demanding task of reference 6 resulted in poorer ratings for the minimum stability region of the short-period mode. Reference 7 points out that minimum boundaries of control are very hard to define, especially in the absence of outside forcing functions, and that results are best obtained by simulating the actual conditions.

The present investigation is an attempt to help define the problems connected with supersonic cruising flight at high altitudes and to obtain pilot ratings for conditions of low stability and damping. In order to investigate the configuration it was first necessary to establish a good control system. The investigation was divided into two parts: studies of the longitudinal stability characteristics and the lateral-directional characteristics. In investigating one mode, the stability and damping of the other mode was increased to a "satisfactory" level. Conditions simulated were Mach 3 cruising flight at an altitude of 70,000 feet. A fixed-base cockpit was used in the tests in conjunction with an analog computer. The pilot was given a task to do and his rating was used to evaluate the configuration. The tasks were routine control problems, such as turns onto headings, straight and level flight, and changes in altitude. The pilot's ratings were in accordance with the Cooper scale of ratings (ref. 8).

SYMBOLS

b wing span, ft

c wing chord, ft

$\bar{c}$ wing mean aerodynamic chord, $\dfrac{\int c^2 dy}{\int c\ dy}$, ft

C_D drag coefficient, $\dfrac{\text{Drag}}{\bar{q}S}$

$C_{D,o}$ drag coefficient at zero lift

$C_{D_{C_L{}^2}}$ drag rise with lift, $\dfrac{\partial C_D}{\partial (C_L{}^2)}$

C_L lift coefficient, $\dfrac{\text{Lift}}{\bar{q}S}$

C_{L_α} airplane lift-curve slope, $\dfrac{\partial C_L}{\partial \alpha}$

$C_{L_{\delta_e}}$ lift variation with elevator deflection, $\dfrac{\partial C_L}{\partial \delta_e}$

C_l rolling-moment coefficient, $\dfrac{\text{Rolling moment}}{\bar{q}Sb}$

C_{l_p} change in rolling-moment coefficient due to rolling velocity, $\dfrac{\partial C_l}{\partial (pb/2V)}$

C_{l_r} change in rolling-moment coefficient due to yawing velocity, $\dfrac{\partial C_l}{\partial (rb/2V)}$

C_{l_β} effective-dihedral derivative, $\dfrac{\partial C_l}{\partial \beta}$, per radian

$C_{l_{\delta_a}}$ roll-control power derivative, $\dfrac{\partial C_l}{\partial \delta_a}$, per radian

C_m pitching-moment coefficient, $\dfrac{\text{Pitching moment}}{\bar{q}S\bar{c}}$

C_{m_q} change in pitching-moment coefficient due to pitching velocity, $\dfrac{\partial C_m}{\partial (q\bar{c}/2V)}$

C_{m_α} static longitudinal stability derivative, $\dfrac{\partial C_m}{\partial \alpha}$, per radian

$C_{m_{\dot{\alpha}}}$ change in pitching-moment coefficient due to angle-of-attack rate, $\dfrac{\partial C_m}{\partial (\dot{\alpha}\bar{c}/2V)}$

$C_{m_{\delta_e}}$ pitch-control power derivative, $\dfrac{\partial C_m}{\partial \delta_e}$, per radian

C_n yawing-moment coefficient, $\dfrac{\text{Yawing moment}}{\bar{q}Sb}$

C_{n_p} change in yawing-moment coefficient due to rolling velocity, $\dfrac{\partial C_n}{\partial(pb/2V)}$

C_{n_r} change in yawing-moment coefficient due to yawing velocity, $\dfrac{\partial C_n}{\partial(rb/2V)}$

C_{n_β} static directional-stability derivative, $\dfrac{\partial C_n}{\partial \beta}$, per radian

$C_{n_{\delta_a}}$ yawing-moment variation with aileron deflection, $\dfrac{\partial C_n}{\partial \delta_a}$, per radian

$C_{n_{\delta_r}}$ yaw-control power derivative, $\dfrac{\partial C_n}{\partial \delta_r}$, per radian

C_Y side-force coefficient, $\dfrac{\text{Side force}}{\bar{q}S}$

C_{Y_β} side-force derivative, $\dfrac{\partial C_Y}{\partial \beta}$, per radian

$C_{Y_{\delta_r}}$ side-force variation with rudder deflection, $\dfrac{\partial C_Y}{\partial \delta_r}$

g acceleration due to gravity, 32.2 ft/sec^2

I_X, I_Y, I_Z moment of inertia about airplane X-, Y-, and Z-axis, respectively, slug-ft^2

M Mach number

n_z normal acceleration, g units

p rolling velocity, radians/sec

q pitching velocity, radians/sec

$\bar{q}$ dynamic pressure, lb/sq ft

r yawing velocity, radians/sec

S wing area, sq ft

τ_R roll time constant, sec

V velocity, ft/sec

W airplane gross weight, lb

y lateral coordinate, ft

α angle of attack, radians

$\dot{\alpha}$ time rate of change of angle of attack, radians/sec

β sideslip angle, radians or deg

δ_a total aileron deflection, positive for right aileron trailing edge down, radians

δ_e elevator deflection, positive for trailing edge down, radians

δ_p longitudinal deflection at control wheel, in.

δ_r rudder deflection, positive for trailing edge left, radians

ζ longitudinal short-period damping ratio

ζ_d damping ratio of the Dutch roll oscillation

φ angle of roll, radians or deg

ω_d undamped natural frequency of the Dutch roll oscillation

ω_φ undamped natural frequency appearing in the numerator of the φ/δ_a transfer function

ω_n undamped longitudinal short-period frequency

DESCRIPTION OF SIMULATOR

The simulator consisted of a fixed-base cockpit and an analog computer. A photograph of the cockpit is shown as figure 1. The cockpit had a conventional control system which consisted of a center yoke, rudder pedals, and a throttle (quadrant). The pilot was presented with no visual or motion cues other than instrument displays. The instrument panel included standard aircraft-type instruments, such as a two-axis attitude gyro and other dial-type indicators for course or course error, indicated airspeed, Mach number, normal acceleration, altitude, rate of climb, angle of attack, and thrust. The control motions, representing inputs to the elevators, ailerons, rudder, and engines, were converted to electrical signals that were fed to the analog computer which was programed for six-degree-of-freedom body-axis equations and characteristics of supersonic transport configurations for the cruise condition at a Mach number of 3.0. Information from the resulting computed aircraft motions or maneuvers were then fed back to the cockpit and displayed on the instrument panel. In addition to providing information for the pilot, the following parameters were recorded for further analysis: angle of attack; sideslip angle; elevator, aileron, and rudder control positions; roll, pitch, and yaw rates; Mach number; altitude; heading; bank angle; and normal acceleration.

Some of the control-system characteristics are illustrated in figure 2 and table I. Shown plotted in figure 2 is the variation with stick deflection of the stick force and the voltage which is fed to the computer. Since the stick was linked directly to a potentiometer, there was no hysteresis or backlash and the voltage gradient was constant. This was also typical of the other controls. The stick force was approximately linear with deflection with a small breakout force and a friction band of less than 2 pounds. The control tended to center within ±0.1 inch. The longitudinal stick-force gradient could be varied from 2 to 16 pounds per inch. Simulated variations in levels of control power were accomplished by varying the voltage gradient from the pilot's controls to the analog.

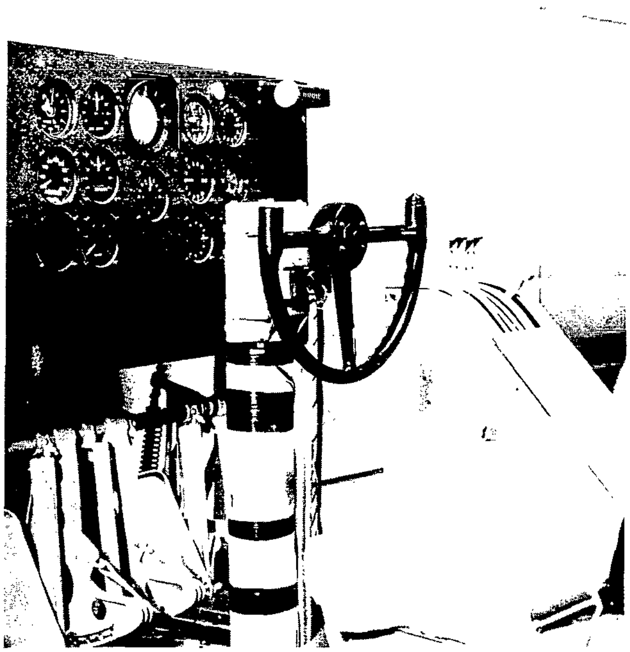

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Figure 1.- Simulator fixed-base cockpit showing instrument panel, throttle quadrant, and elevator, aileron, and rudder controls.

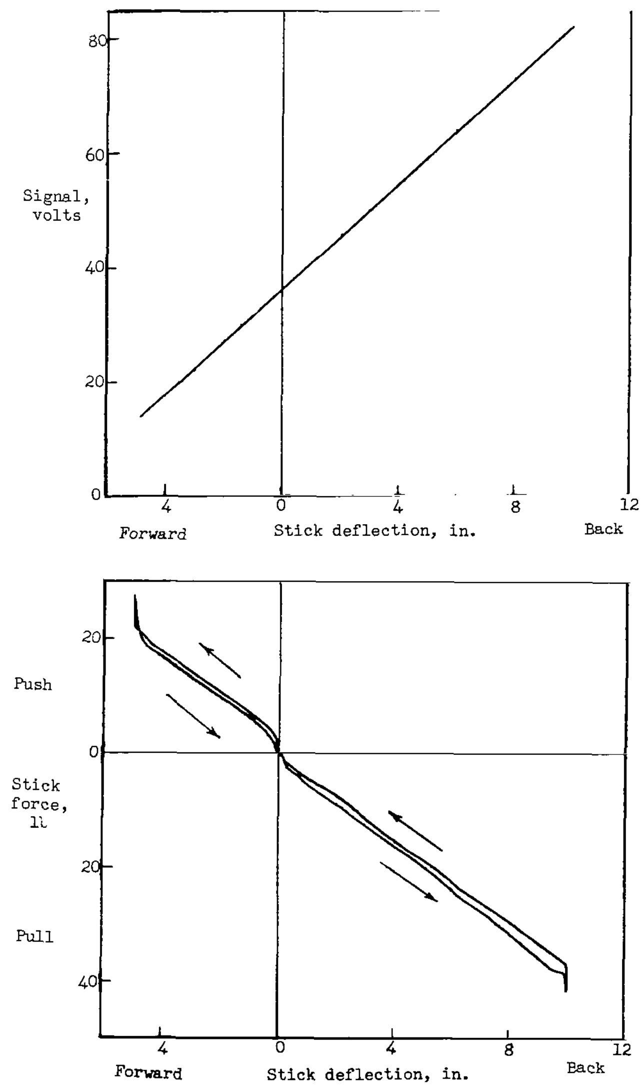


Figure 2.- Variation of signal voltage and control force with control deflection.

TABLE I.- COCKPIT CONTROL-SYSTEM CHARACTERISTICS

Control system	Range	Breakout force, lb	Force gradient	Damping	Max. force, lb
Longitudinal	5 in. forward 10 in. back	2	Constant	0.7 critical	20 to 160
Lateral (wheel)	±85°	2	Constant	None	30
Directional (pedals)	±4 in.	0	Constant	None	150

TESTS

Range of Configuration Characteristics

The basic (unaugmented) simulated airplane characteristics are presented in table II. These characteristics were obtained from analytical results and wind-tunnel tests of a variable-sweep-wing configuration. For the present investigation pertinent basic characteristics were varied to give a change in desired simulated dynamic characteristics. Some of the dynamic characteristics are presented in table III. The longitudinal short-period frequency and damping ratio for the basic configuration were 0.37 cps and 0.06, respectively. In the longitudinal investigation the short-period frequency was varied from 0.37 to 0.13 cps by assuming decreased values of the static longitudinal stability derivative C_{m_α}. Values of damping in pitch C_{m_q} were generally increased from the basic value to obtain damping ratios of 0.06 to 0.36, as noted in table III. Also, for the longitudinal investigation, values of damping in roll C_{l_p} and values of damping in yaw C_{n_r} were increased to give the roll time constant τ_R of 1.00 and Dutch roll damping ratio ζ_d of 0.27 (table III).

For the lateral-directional investigation, the longitudinal frequency was decreased to 0.31 cps by decreasing the value of C_{m_α} and the longitudinal damping ratio ζ was increased to 0.43 by increasing the value of C_{m_q}. Values of aileron control sensitivity were investigated, and values of aileron yawing moment per aileron rolling moment were investigated for the basic lateral-directional configuration and for configurations with improved roll and yaw damping. For the basic configuration, the roll time constant was 4.7 sec and the Dutch roll damping ratio was 0.06 of critical. Increasing the basic value of C_{n_r} by a factor of 5 reduced the roll time constant to 2.9 sec and increased the Dutch roll damping ratio to 0.12 of critical. (See table III.) Increasing the basic value of C_{l_p} by a factor of 3 reduced the roll time constant to 1.8 sec and increased the Dutch roll damping ratio to 0.15 of critical. Increasing both C_{n_r} and C_{l_p} the specified amounts resulted in a roll time constant of 1.4 sec and Dutch roll damping ratio of 0.22 of critical. For these changes in C_{n_r} and C_{l_p}, the value of Dutch roll

TABLE II.- CHARACTERISTICS OF BASIC (UNAUGMENTED) SIMULATED AIRPLANE

W, lb	300,000
S, sq ft	4,040
b, ft	76.8
$\bar{c}$, ft	62.73
C_{L_α}	1.55
$C_{L_{\delta_e}}$	0.375
$C_{m_{\delta_e}}$	-0.25
C_{m_α}	-0.36
C_{m_q}	-1.04
$C_{m_{\dot{\alpha}}}$	0.30
C_{l_p}	-0.125
$C_{l_{\delta_a}}$	-0.011
C_{l_r}	0.102
C_{l_β}	-0.0862
I_X, slug-ft^2	1,000,000
I_Y, slug-ft^2	10,000,000
I_Z, slug-ft^2	11,000,000
C_{n_β}	0.075
C_{n_r}	-0.453
C_{n_p}	0.014
$C_{n_{\delta_r}}$	-0.028
$C_{n_{\delta_a}}$	-0.0092
C_{Y_β}	-0.347
$C_{Y_{\delta_r}}$	0.042
$C_{D,o}$	0.0082
$C_{D_{C_L^2}}$	0.585
$\frac{\partial C_m}{\partial C_L}$	0.232

TABLE III.- CONFIGURATION DYNAMIC CHARACTERISTICS

Configuration	Short-period mode		Dutch roll mode			Roll mode
	Frequency, ω_n, cps	Damping ratio, ζ	Frequency, ω_d, cps	Damping ratio, ζ_d	Roll-sideslip ratio, φ/β	Time constant, τ_R, sec
Basic (unaugmented)	0.37	0.06	0.25	0.06	6.36	4.7
Longitudinal	.37	.06	.24	.27	6.36	1.00
	.37	.11	.24	.27	6.36	1.00
	.31	.14	.24	.27	6.36	1.00
	.31	.22	.24	.27	6.36	1.00
	.26	.08	.24	.27	6.36	1.00
	.26	.17	.24	.27	6.36	1.00
	.26	.26	.24	.27	6.36	1.00
	.26	.36	.24	.27	6.36	1.00
	.13	.08	.24	.27	6.36	1.00
	.13	.16	.24	.27	6.36	1.00
	.13	.26	.24	.27	6.36	1.00
	.13	.36	.24	.27	6.36	1.00
Lateral-directional	.31	.43	.25	.06	6.36	4.7
	.31	.43	.25	.12	6.36	2.9
	.31	.43	.24	.15	6.36	1.8
	.31	.43	.24	.22	6.36	1.4

frequency was approximately 0.25 cps. To investigate roll-control sensitivity the aileron rolling moment per radian wheel deflection was varied while keeping constant the ratio of aileron yawing moment to rolling moment. In the aileron yawing-moment investigation, the ratio of aileron yawing moment to aileron rolling moment was varied from approximately -1 to 3.4.

In the lateral-directional investigation, Dutch roll characteristics were not a primary variable; the results of reference 6 indicated that improving the yaw damping would place the Dutch roll characteristics in the satisfactory range. The basic value of roll-sideslip ratio of 6.36 was used throughout the evaluation. According to reference 9, the basic value of roll-sideslip ratio was tolerable for the basic value of Dutch roll damping ratio and satisfactory when Dutch roll damping was increased.

Longitudinal Control Sensitivity

The procedure used in the tests was to make a series of runs with various control sensitivities for each configuration of stability and damping in an effort to determine a satisfactory value of control sensitivity for the configurations being rated. Control sensitivity was varied to result in values of normal acceleration per inch stick deflection n_z/δ_p of 0.05, 0.1, 0.2, 0.4, and 0.8, although not all values were used for each configuration. The majority of runs were made with a constant force gradient of 4 lb/in. stick deflection. Holding the force gradient constant (4 lb/in.) for various levels of control power resulted in varying values of force per g from 5 to 80 lb/g. Some later runs were made varying control sensitivity and holding a constant force per g of 40 lb/g.

Tasks for Configuration Evaluation

Separate tasks were set up for pilot evaluation of the controllability of the longitudinal and lateral-directional modes. In both modes, a cruise condition was set up for a Mach number of 3.0 at an altitude of 70,000 feet. For the evaluation of the longitudinal mode, the task consisted of a 15° turn, 1 minute of straight and level flight, and a descent of 5,000 feet followed by another minute of straight and level flight. In the tasks for a lateral control evaluation, an initial heading error was introduced. This error required the pilot to maneuver the airplane laterally to intercept and establish the airplane on the desired course radial. Once this was accomplished, the pilot continued on course straight and level for several minutes to complete the run. In all turns and level flights, the pilot was to hold a specified altitude and Mach number. During the tests, the pilot attempted to operate the simulator with a minimum of normal and lateral acceleration as would be desirable in a transport airplane with passengers aboard. The configurations were rated according to the system presented in table IV.

TABLE IV.- PILOT OPINION RATING SYSTEM

	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition	No	Doubtful
		8	Unacceptable - dangerous	No	No
		9	Unacceptable - uncontrollable	No	No
	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

Pilots Used in Evaluation

For most of the configurations, two pilots rated each configuration. For a small number of configurations three pilots rated each configuration, and for a small number of configurations only one pilot rating was obtained. The pilots are experienced test pilots with experience in handling-qualities evaluation of fighters and transports and in simulation work. Two pilots have 12 to 15 years of flight-test experience each and the third pilot has approximately 5 years.

RESULTS AND DISCUSSION

Longitudinal Mode

Control sensitivity.- Some typical pilots' evaluations of several configurations are shown in figure 3 in which pilot's rating is plotted against the stick sensitivity parameter n_z/δ_p for a constant force gradient of 4 lb/in. stick deflection. Optimum control sensitivities which are minimum pilot ratings are indicated for most of the configurations shown. Variations in the rating are evident between pilots and also for a given pilot on repeated tests. The variations are within about ±1 numerical rating from the average. These variations in rating are expected.

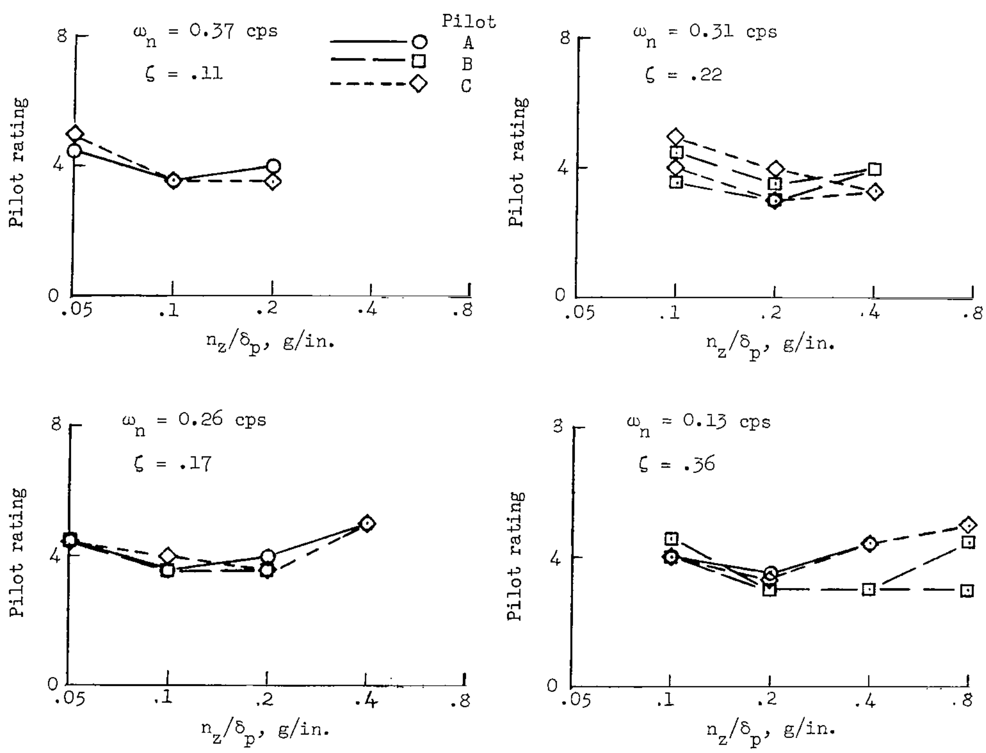


Figure 3.- Sample pilot evaluations as a function of longitudinal stick sensitivities n_z/δ_p for configurations of short-period frequency and damping.

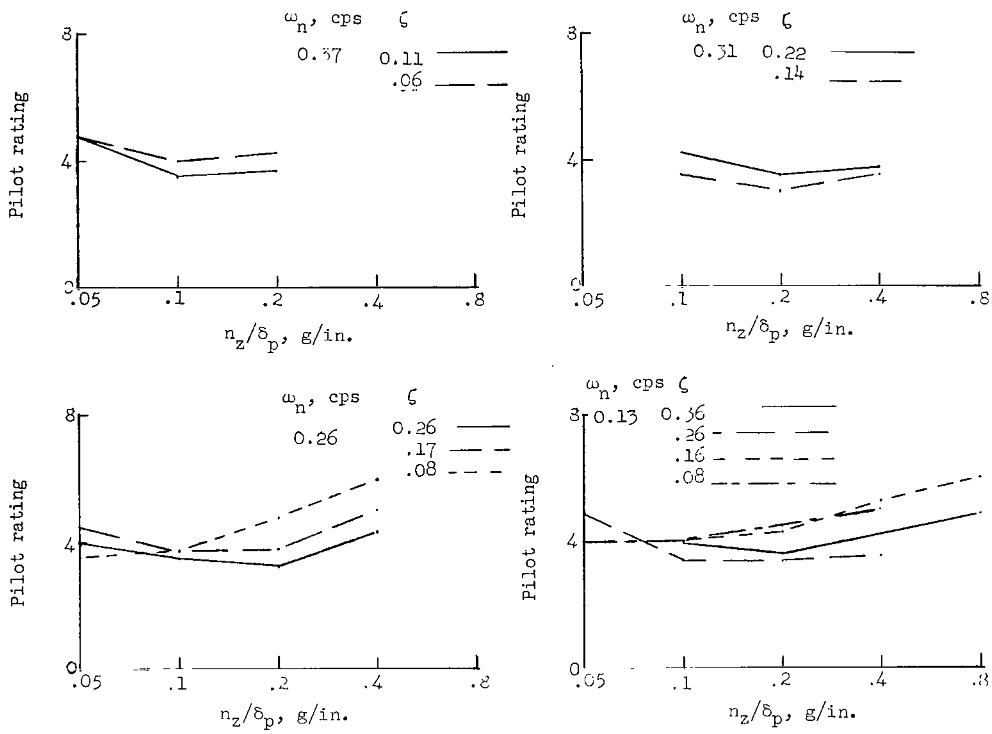
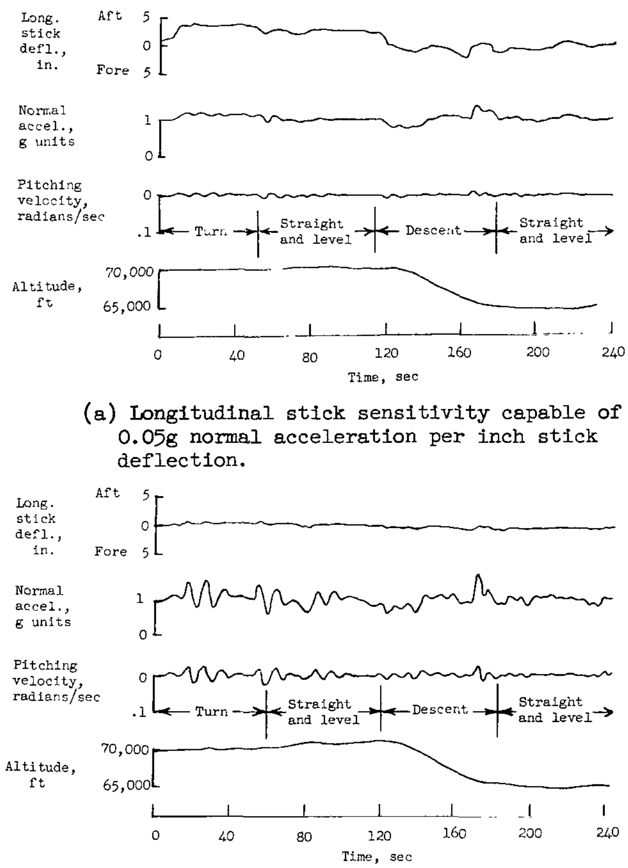


Figure 4.- Average pilot ratings as a function of longitudinal stick sensitivities n_z/δ_p for specific configurations of short-period frequency and damping.

The average of all the pilots' ratings is presented in figure 4 for the various stability-augmented configurations tested. The averages are for two or more pilots for most of the configurations. At the lower frequencies, ω_n = 0.26 and 0.13 cps, a range of damping ratios ζ from 0.08 to 0.36 was studied. At the higher frequencies, ω_n = 0.31 and 0.37 cps, only the effect of the lower damping ratios was checked. Although the results are incomplete, a preferred control sensitivity region is shown for most of the configurations in the figure. This preferred control sensitivity region occurs generally at values of n_z/δ_p from 0.1 to 0.2g/in. and has a pilot rating of 3 to 4 which borders on the unsatisfactory.

There is also indicated in the figure that preferred control sensitivity increases with increase in configuration damping as would be expected. The effect of control sensitivity on pilot performance is best illustrated by the time histories of quantities recorded during two runs presented in figure 5. The runs illustrate typical piloting tasks consisting of a turn, straight and level flight, descent, and straight and level flight. The configuration has a short-period frequency of 0.13 cps and a damping ratio of 0.16. In figure 5(a) the stick sensitivity was such that the pilot could obtain 0.05g normal acceleration per inch stick deflection, whereas in figure 5(b) the pilot could obtain 0.8g normal acceleration per inch. In figure 5(a) the maximum control motion used was on the order of 4 in. rearward to 2.5 in. forward. This range of stick motion was appreciated by the pilot (pilot rating of 4) and resulted in a fairly smooth flight despite the low configuration damping. Maneuvering accelerations were 0.2g or less in the turn and ±0.3g in push-over and level off. In figure 5(b) the stick motion was small (< ±1 inch) and was disliked by the pilot (pilot rating of 6). The pilots commented that this combination of high stick sensitivity and poor configuration damping resulted in oscillations and overcontrol. Levels of normal-acceleration disturbance were ±0.7g with almost continuous oscillations. These levels of acceleration are sometimes possible on a fixed-base simulator where the pilot is concentrating on other tests. In actual flight, however, kinesthetic motion cues would have aided the pilot in obtaining a smoother flight even at the expense of accuracy in altitude control.

Control force.- In the rating of a control system, the forces connected with control deflection exert a marked influence. Initial runs were made with a constant force gradient of 4 lb/in. stick deflection. Holding the force gradient constant (4 lb/in.) for various levels of control power resulted in varying values of force per g from 5 to 80 lb/g. For the optimum region of pilot rating, the values of force per g were 20 to 40 lb/g. These values are low in accordance



(a) Longitudinal stick sensitivity capable of 0.05g normal acceleration per inch stick deflection.

(b) Longitudinal stick sensitivity capable of 0.8g normal acceleration per inch stick deflection.

Figure 5.- Time histories of pilot input and SST simulator responses for two values of longitudinal control sensitivity. M = 3.0; 70,000-foot altitude; ω_n = 0.13 cps; ζ = 0.16.

with Military Specification (ref. 9) when based on a limit load factor of 2.5 but are of the same order of magnitude as those previously determined to be desirable from a flying-qualities standpoint in a large bomber-type airplane (ref. 10). This low value of control-force gradient may tend to endanger the structural integrity of aircraft with low limit load factors; for this type of aircraft, a means of load limitation other than the normal control-force gradient is indicated. To determine whether there was any separate effect on the pilot ratings of varying force per g while varying control-power gradients, some sample runs were made with a constant force per g of 40 lb/g. This force per g corresponds to the upper value previously mentioned for the optimum region and resulted in higher stick forces per inch for the control-power gradients above the optimum region. The data for the low control-power gradients (below 40 lb/g) were inconclusive. Establishing the proper control-system characteristics was necessary in obtaining the pilot's optimum level of performance and, hence, rating of the overall system.

Configuration frequency and damping.- Pilot ratings for various configuration frequencies and damping are presented in figure 6. The ratings are the average ratings which were presented in figure 4 for a control sensitivity of 0.1 g/in. Pilot ratings vary from 3.4 to 4.3 with no general trend being established. Presented in figure 6 are also pilot ratings from reference 5, a "good" rating corresponding to a pilot rating of 1.5 and two "satisfactory" ratings corresponding to a pilot rating of 3.5. The present investigation and the results of reference 5 indicate qualitative agreement for the "satisfactory" ratings.

General comments.- The pilot required a period of adaptation with the supersonic transport fixed-base simulator. The adaptation period enabled the pilot to become familiar with the simulator and to recognize the flight problems peculiar to the SST in cruising flight.

The pilots commented on the large changes in rates of climb resulting from small changes in pitch angles. At $M = 3$ a change in pitch angle of 1° results in a rate of change of altitude of approximately 3,000 ft/min. This rate of change is over three times the rate of change in altitude for a change of 1° in pitch angle experienced by a subsonic jet transport. This characteristic increased the difficulty of holding a specific altitude for level flight, as illustrated in figure 5(b). After the turn segment of the run, the pilot departed from the assigned altitude by 1,000 feet. It should be noted that these departures did not

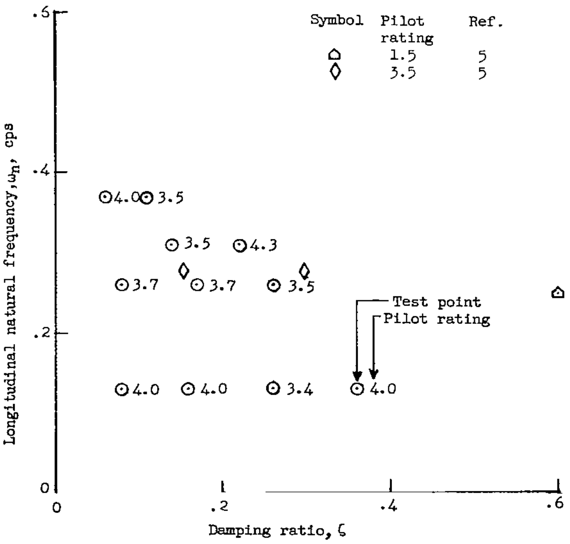


Figure 6.- Average pilot ratings for various levels of configuration frequency and damping for a control sensitivity of 0.1 g/in.

necessarily occur only for cases with poor pilot ratings. An examination of the records taken during the pilot's evaluation runs revealed that the pilot departed from the preassigned altitude by at least 500 feet during 80 percent of the runs. The pilots commented that these departures were a result of out-of-trim conditions or preoccupation with trimming, changing flight path, and so forth. The departures from specified flight conditions are caused, in part, by the large lead times necessary to change the direction of the velocity vector without incurring large accelerations. This factor points to the necessity of recognizing the altitude deviation quickly so that the pilot can take action as soon as possible.

In fixed-base simulation, the pilot must rely on his instruments to portray the flight conditions and departures from flight conditions. In controlling the supersonic transport in cruising flight, the pilot changed his techniques as he became familiar with the instruments and flight characteristics. The small changes in pitch attitude angles required to trim the aircraft made the attitude indicator practically useless for precise control. To trim the aircraft, the pilot frequently utilized the rate of climb indicator and the acceleration indicator because of their increased sensitivity over the attitude indicator. The altimeter, Mach number indicator, thrust indicator, and trim indicators were also used in establishing longitudinal flight conditions. Pilots' comments indicated that in maneuvering flight the acceleration indicator was one of the primary instruments used. Changes in flight path were first noted on the acceleration indicator and then as changes in rates of climb or descent. In flight, the pilot would probably sense acceleration and would use the g meter in ascertaining values of acceleration.

Lateral-Directional Mode

Lateral mode.- The lateral-directional investigation consisted of varying rolling-mode characteristics such as roll time constant, aileron control-power gradient, and aileron yawing moment. Various aileron control-power gradients and roll time constants are presented in figure 7 for ailerons that induce very little yaw disturbances, $(\omega_\varphi/\omega_d)^2 = 0.9$. The data show that configurations having roll time constants τ_R of 4.7 sec are acceptable (pilot ratings of 3.5 to 4.0). The configuration was improved with the reduction in roll time constant from 4.7 to 1.8 or 1.4. The reduction in roll time constant resulted in a reduction in attention to the rolling mode by the pilot and better precision in flying. Pilot ratings of 2 on the scale were obtained for $\tau_R = 1.4$ (fig. 7). With the improvement in roll damping the pilot preferred an aileron control-power gradient of approximately 2 radians/sec^2/radian which is

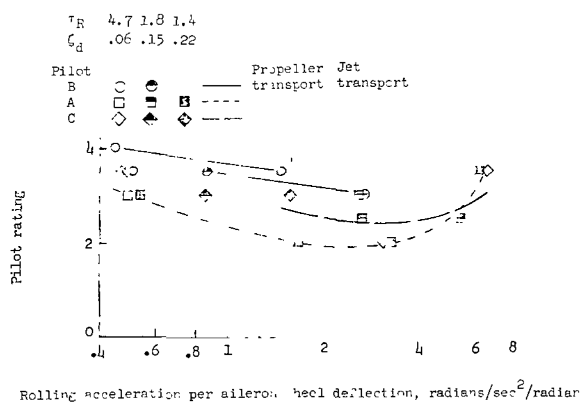


Figure 7.- Effect of aileron control-power gradient on pilot rating for aileron configurations giving small yaw disturbances. $(\omega_\varphi/\omega_d)^2 = 0.9$.

comparable to that for present-day transports (one propellor and one jet) in cruising flight. The data of figure 7 are presented in terms of aileron control-power gradient rather than maximum control power because of the nature of the control motion. It was noted that during the tasks performed by the pilot, aileron control motion rarely exceeded 10 to 20 percent of maximum.

Aileron cross coupling.- The various levels of aileron-induced yaw disturbances were evaluated by a parameter $(\omega_\varphi/\omega_d)^2$ used in reference 3. This parameter is the ratio of the squares of the natural frequencies appearing in the transfer function of roll-angle response to aileron deflections. For $(\omega_\varphi/\omega_d)^2 = 1$, induced yaw disturbances are a minimum. For $(\omega_\varphi/\omega_d)^2 < 1$, induced yaw is in the adverse direction; for $(\omega_\varphi/\omega_d)^2 > 1$, induced yaw is in a proverse direction increasing with increase in value of $(\omega_\varphi/\omega_d)^2$ from 1. The data are presented in figure 8 for $(\omega_\varphi/\omega_d)^2$ as a function of ζ_d. Pilot ratings are also shown in the figure. The data are presented for values of roll time constant τ_R of 4.7 and 1.8 to 1.4 for two values of Dutch roll damping. Only a few pilot ratings were obtained for $\tau_R = 4.7$ and these ratings tended to substantiate those of reference 3. For $\zeta_d = 0.15$, $\tau_R = 1.8$, and $(\omega_\varphi/\omega_d)^2 = 0.9$, satisfactory pilot ratings of 2.5 were obtained. For $(\omega_\varphi/\omega_d)^2 < 0.9$, an unsatisfactory pilot rating of 4.5 was obtained.

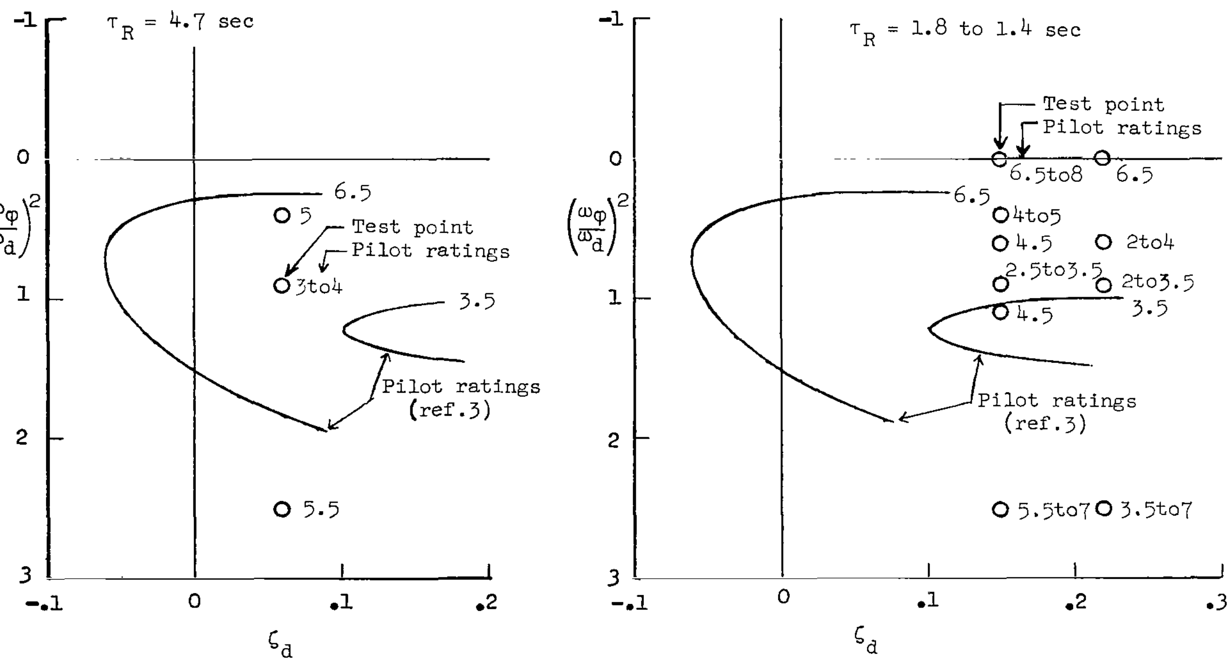


Figure 8.- Aileron yaw characteristics (given as the squares of the natural frequencies of the rolling response to aileron input transfer function) as a function of the Dutch roll damping ratio for two levels of roll time constant.

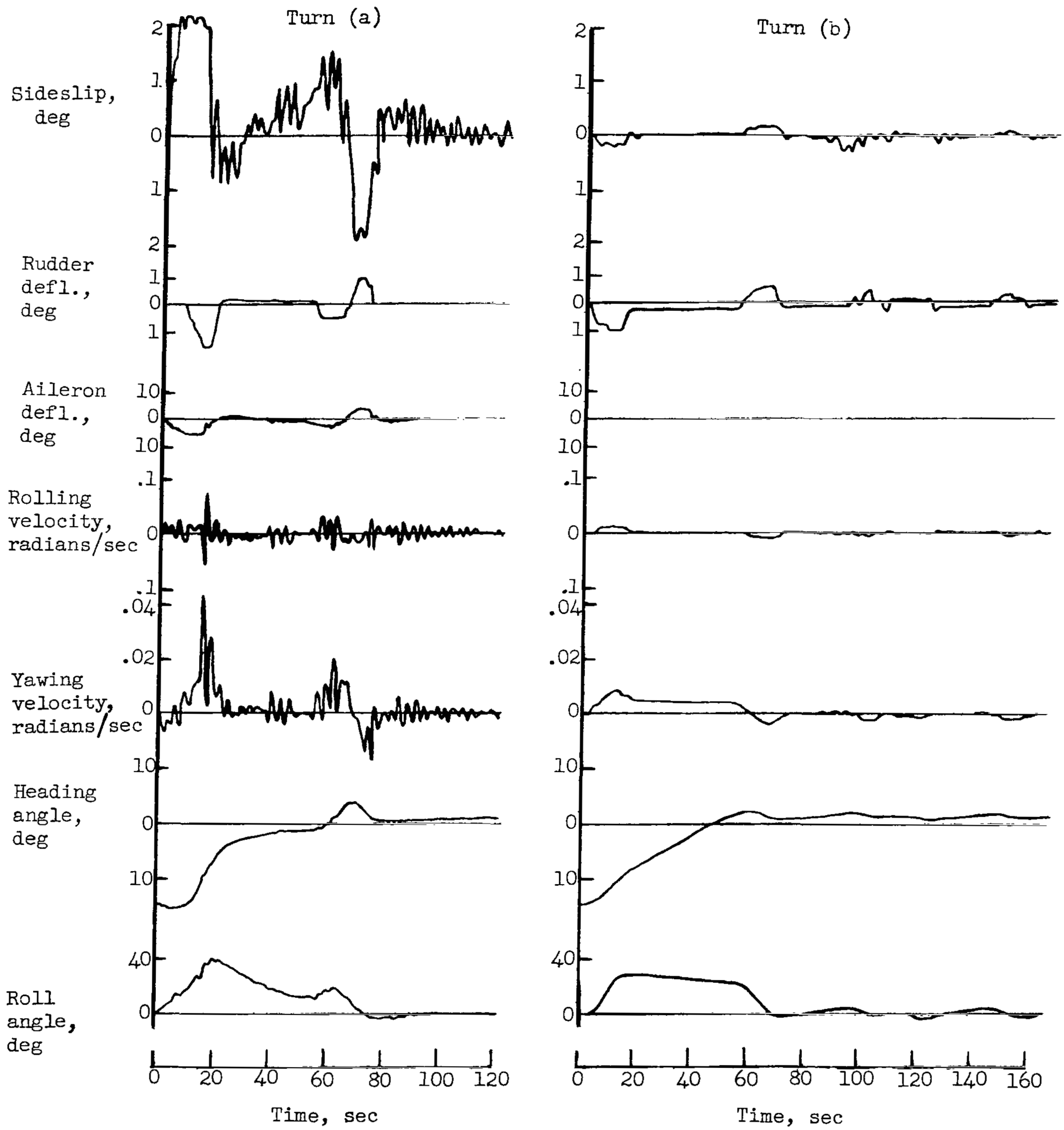


Figure 9.- Time histories of turns onto heading for an airplane configuration having large aileron-induced yawing moment. $(\omega_\varphi/\omega_d)^2 = -0.01$. (Turn (a) was made with ailerons and rudder in a conventional manner to control roll. Turn (b) was made with rudder only to control roll.)

In this region the hesitation in roll caused by the aileron-induced adverse yaw was objectionable to the pilots. For $(\omega_\varphi/\omega_d)^2 = 0$, the aileron induced enough sideslip when normal control techniques were used to completely counteract the aileron roll power. This aileron-induced sideslip resulted in a condition which is intolerable to the pilot (pilot ratings of 6.5 to 8). Time histories of several runs are presented in figure 9 in which the pilot first used the ailerons and rudder in a normal coordinated manner to control roll (Turn (a)) and then used rudder only to control roll (Turn (b)). A smoother and more precise maneuver is evident in Turn (b) where the aileron was not used and the high sideslip due to low $(\omega_\varphi/\omega_d)^2$ was not generated. For $(\omega_\varphi/\omega_d)^2 > 1$, the proverse yaw results in cross control by the pilot (applying rudder opposite to turn) and, hence, less favorable pilot ratings.

For $(\omega_\varphi/\omega_d)^2 = 2.5$ and $\zeta_d = 0.22$, there was a large variation in pilot rating from 3.5 to 7.0 (fig. 8). These variations in pilot rating can be attributed to effects of aileron control power and methods of pilot evaluation. For low values of aileron control power the proverse yaw developed was small and did not appreciably affect the pilot's ability to accurately control roll angle. For large values of aileron control power the pilot tended to use larger aileron inputs, and proverse sideslip angles up to $\pm 2^\circ$ were noted which resulted in excitation of a Dutch roll oscillation that was difficult for the pilot to control. To aid the pilot in evaluating the yaw disturbance, a sideslip meter was included in the instrumentation. Still the pilot could not control sideslip precisely but did control the roll resulting from high roll-sideslip ratios.

CONCLUDING REMARKS

An investigation was made of the pilot's ability to control a fixed-base simulated supersonic transport at a Mach number of 3 and an altitude of 70,000 feet, with emphasis on regions of low stability and damping characteristics. Routine tasks such as changing heading, changing altitude, and maintaining constant altitude flight were used. No outside disturbances were employed in the investigation. The investigation was divided into two parts: studies of the longitudinal stability characteristics and the lateral-directional characteristics. In investigating one mode the stability and damping of the other mode was increased to a "satisfactory" level. This procedure should tend to give more favorable ratings than would be obtained with no improved stability or damping about any axis.

Pilot ratings of the longitudinal stability and control characteristics were generally "acceptable" (pilot rating of 4) for configurations having short-period frequencies of 0.13 to 0.37 cps, damping ratios of 0.06 to 0.36, and compatible control characteristics. Pilots preferred longitudinal stick sensitivities of 0.1 to 0.2g/in. stick deflection and stick-force gradients of approximately 20 to 40 lb/g normal acceleration.

Configurations having roll time constants as high as 4.7 seconds were acceptable, provided good aileron characteristics were established. A decrease in roll time constant from 4.7 sec to 1.8 or 1.4 sec was highly beneficial in improving roll control. The optimum level of aileron-control power gradient (radians/sec^2/radian) for supersonic transport configurations with improved roll damping was similar to that of a present-day turbojet transport in the cruise condition. Aileron-induced yaw disturbances were undesirable.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 2, 1964.

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